

# Quantifying Sustainability Trade-offs in Solar-Driven Biofuel Systems using Life Cycle Assessment

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In 2022, the shipping and aviation industries emitted 706 Mt and 436.7 Mt CO<sub>2</sub> respectively, with more than 99% of energy consumption in both sectors derived from fossil fuels (IEA, 2023b). These emissions contribute significantly to global warming, highlighting the urgent need for sustainable energy solutions. To achieve zero-emission targets, the share of biofuels in shipping and aviation is projected to increase from 0% to 8% and 9%, respectively (IEA, 2023a). Developing novel fuel pathways that are economically, environmentally, and socially sustainable are key to achieving these targets. The ALGAESOL project supports the transition to low-carbon transport by developing sustainable, solar-powered biofuels for shipping and aviation.

ALGAESOL develops three sunlight-driven value chains that convert CO<sub>2</sub> and solar energy into fuels (Figure 1). A photoelectrochemical (PEC) chain employs photoanodes to oxidize water and power electroreduction of CO<sub>2</sub> to methanol, followed by membrane pervaporation for methanol recovery. A photobioelectrochemical (PBEC) chain couples PEC with a bioelectrochemical system (BES), where microbial cathodes reduce CO<sub>2</sub> to methane, which is purified by membrane gas separation. A third chain combines microbial electrosynthesis of acetate with mixotrophic microalgae cultivation, which is treated by membrane dewatering, lipid extraction and hydrogenation to produce sustainable aircraft fuel (SAF). Residual biomass is further valorized by anaerobic digestion BES (AD-BES), producing methane.

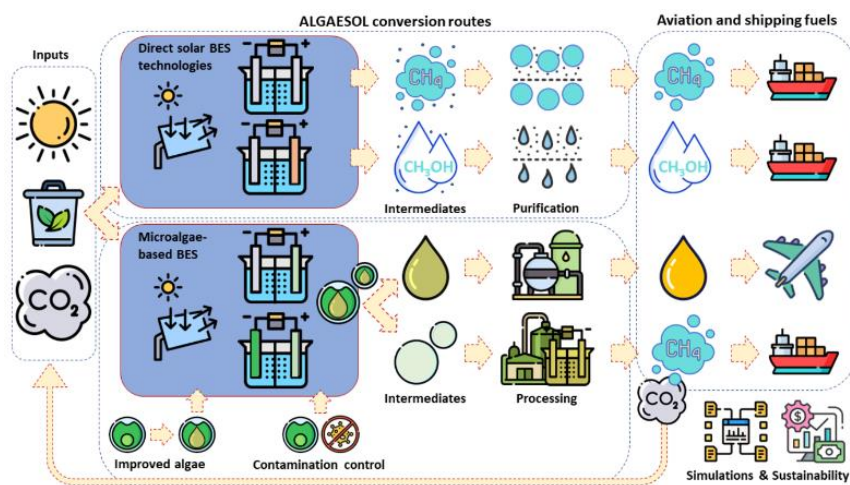


Figure 1: Schematic view of all value chains in the ALGAESOL project.

Integrating sustainability considerations and understanding scale-up dynamics from early design stages is essential both for commercialization and for ensuring the environmental and social robustness of emerging fuel pathways. Sustainable design reduces material consumption, energy use, and waste, while enhancing product competitiveness and customer acceptance. In ALGAESOL, we implement iterative sustainability assessments in two phases: Optimization (to compare scale-up and design options within each value chain) and improvement (to benchmark the best-performing option against state-of-art fuels), based on cradle-to-gate system boundaries and energy-based functional units.

Table 1 shows a selection of alternative technological set-ups that have been compared in the sustainability assessments so far. Process-level technological performance characteristics, (specific energy, conversion efficiencies, material composition and productivity) and cost data (bill of materials and quotes by providers) are derived directly from the project experiments and used in the inventory modelling.

Table 1: Selected alternative technologies evaluated in sustainability assessments.

Technology	Alternatives
Photoanode	Large bath coating (LBC)
	Screen printing (SP)
	Electrodeposition (ED)
Biomass concentration	Pre-concentration with nanofiber filters
	Centrifuge only

For photoanodes, data of fabrication methods were extracted from lab protocols, which were based on scalable methods. Consumption of reagents was scaled up linearly. Energy density of electrodeposition was calculated based on the total charge passed over time and the voltage of the currents. Thermal loads were balanced according to thermodynamic equations described in Table 2.

Table 2: Thermodynamic equations used to describe the thermal processes required to fabricate photoanodes using three different methods.

Thermal process	Equation
Heat up mass	$m c_p \Delta T$
Heat transfer in oven and bath	$A U \Delta T \Delta t$
Evaporate mass	$h_{vap} m$

Preliminary results indicate that LBC fabrication is the least energetically demanding. Although the incident photon current efficiency (ICPE) of the photoanode material used in the LBC and SP setups was initially lower compared to the material used for ED, they can achieve similar photocurrents under 1 sun with additional doping. However, including the costs of the rare earth metal required for doping increased the overall production costs significantly, ultimately favoring SP in cost.

Biomass dewatering by filtration and centrifugation was benchmarked against dewatering solely with centrifugation. Specific energy of the membrane was calculated according to Bilad et al., 2012:

$$E_{\text{filter}} = P_{\text{in}} + P_{\text{p}} + r_A(A_c + C_a + CIP)$$

Where  $P_{\text{in}}$  and  $P_{\text{p}}$  are specific energies for influx and permeate pumping respectively,  $r_A$  is a ratio between membrane flux and reference flux, and  $A_c$ ,  $C_a$ ,  $CIP$  are specific energies for aeration, compression and cleaning in process (CIP) respectively. Data on permeability and operational transmembrane pressure was extracted by experimental results and used to calculate the membrane flux. Results indicate that filtration can save >50% energy compared to centrifugation only.

Initial findings reveal key trade-offs among the ALGAESOL value-chains and are already guiding development toward more sustainable configurations. As these results can be sensitive to scale-up and performance uncertainties, upcoming work will quantify these uncertainties and benchmark the optimized pathways against state-of-the-art fuels.

## References

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